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The Core of a Blazar Jet

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Abstract. The nature of the bright upstream end of jets as seen in VLBI images, known as the core, is difficult to specify because it is only weakly resolved on the images. Here the author discusses evidence indicating that the core is either where the optical depth is of order unity or a standing shock somewhat farther downstream. The jet at this point is turbulent, causing the polarization to be low and variable. At short millimeter wavelengths where the overall continuum spectrum turns over, the core should be at or just downstream of the zone where the flow is accelerated and collimated.

1. Introduction

One of the primary goals of blazar studies is to determine how their jets form, collimate, and accelerate to relativistic flow speeds. Pursuit of this aim involves imaging in total and polarized intensity at submilliarcsecond resolution with very long baseline interferometry (VLBI). However, even millimeter-wavelength VLBI is insufficient to resolve fully the core that lies at the upstream end of a jet on the images. Although this has slowed progress, recent studies of time variability of the images are now revealing the nature of the jet in the core region. This paper summarizes evidence that indicates that in many cases the core is a standing conical shock at a point where the jet flow is highly turbulent.

2. Observations of the Core

According to standard wisdom (see Blandford & Königl 1979; Königl 1981), what is seen as the core on centimeter-wave VLBI images should be the section of the jet where the optical depth is roughly unity (the "$\tau \sim 1$ surface"). In that case, the observed brightness temperature measures the ratio of relativistic electron to magnetic energy density (Readhead 1994). Kovalev et al. (2005) have analyzed the VLBA visibility data of a large sample of sources with cores that are partially resolved both in the direction along and transverse to the jet axis. Homan et al. (2006) have analyzed this dataset, finding that — except during outbursts when a new superluminal knot may be passing through — the magnetic and relativistic electron energy densities in the core are typically near equipartition.

If what is seen as the core on VLBI images is the $\tau \sim 1$ surface, the position of the core should move toward the central engine at higher frequencies. This effect is apparent in some (compact) extragalactic jets (e.g., Lobanov 1998), but not in others (e.g., Mittal et al. 2006). The latter negative result implies that the jet contains multiple bright stationary features in addition to superluminally moving knots. Indeed, time sequences of 22 and 43 GHz images reveal that stationary features downstream of the core are common in blazar jets (Jorstad et al. 2001, 2005). At progressively lower frequencies, the $\tau \sim 1$ surface moves toward and then passes a given stationary hotspot, so that the "core" is either the hotspot or the $\tau \sim 1$ surface, or a combination of the two.

The polarization of the core can provide valuable clues regarding its nature. Figure 1 presents a sequence of images of the parsec-scale jet of 3C 273 at 43 GHz obtained with the Very Long Baseline Array (VLBA). The polarization across the image is indicated, as is the polarization at 230 GHz integrated over the entire source. Note that the core is unpolarized on the image. This could indicate either (1) a highly tangled magnetic field, (2) two components in the core with equal polarized flux density but with polarization directions that are transverse to each other, or (3) Faraday depolarization. The correspondence of the polarization position angle at 230 GHz with that of the first bright knot in the jet at 43 GHz implies that the core contributes little to the polarization at the higher frequency. Since it would be fortuitous for two cross-polarized components in the core (where optical depth effects play a role) to have identical polarized flux density at the two frequencies, one can reject option (2) as highly unlikely. One can eliminate option (3) as well, since this object often contains new superluminal knots with significant polarization at 43 GHz just as they start to emerge from the core region. In addition, 230 GHz is a rather high frequency for Faraday effects to play such a dominant role in the degree of polarization.

3. Models for the Core

It is important to note that the "core" in VLBI images is generally *not* the base of the jet. While the jet appears to be roughly self-similar on parsec scales, it cannot remain so all the way down to the launching site adjacent to the central engine (Marscher 1995). Otherwise, the spectral turnover $\nu_{\rm m}$ would be at IR or optical frequencies rather than the observed range of $3 \times 10^{11\pm1}$ Hz (Impey & Neugebauer 1988; Bloom et al. 1999). The angular width of the jet at this point can be estimated by the value at 43 GHz, ~ 50 μarcsec times 43 GHz/$\nu_{\rm m}$. For a quasar with redshift of order 0.5, this translates to $\sim 0.3(43\ {\rm GHz}/\nu_{\rm m})$ pc, which is small (a few 10^{16} cm for $\nu_{\rm m} \sim 1000$ GHz) but still hundreds of gravitational radii even for $M_{\rm BH} \sim 10^9\ {\rm M}_\odot$. This is just the width of the jet; the distance from the black hole is even larger since the jet is at least somewhat focused within this point. Because the 43 GHz core is even farther downstream, it is possible that the jet is controlled by an ordered magnetic field within the main acceleration and collimation zone and becomes turbulent and near equipartition thereafter. How this occurs over a fairly short distance presents a theoretical challenge. Perhaps velocity shear — which is expected in magnetic acceleration models (e.g., Vlahakis & Königl 2004) — generates turbulence that eventually brings the initially magnetically dominated plasma into rough energy equipartition. Such velocity shear is observed in 3C 273 (Jorstad et al. 2007).

What can cause the jet to have its brightest spot well downstream of its launching site? One possibility is that the acceleration of the flow is gradual, so that the greatest Doppler beaming occurs some distance from the central

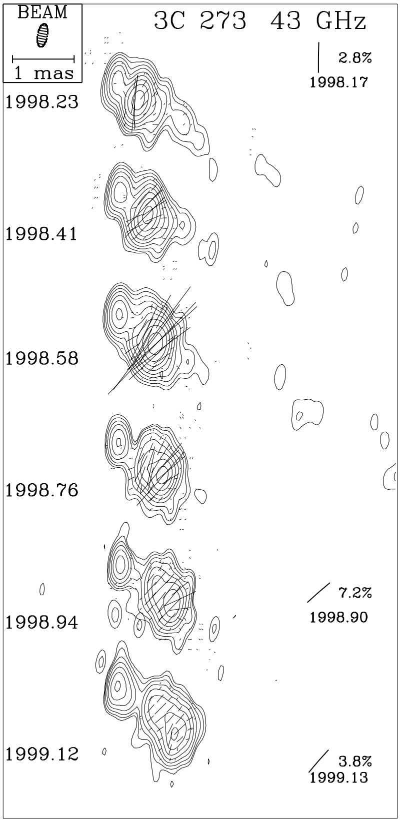

Figure 1. Sequence of VLBA images of the quasar 3C 273 at 43 GHz. The core is the bright feature on the eastern end (*left*) of the jet. The polarization vectors are indicated by the line segments. The date of each observation is given in decimal years. The line segments to the right give the polarization at 230 GHz as observed with the James Clerk Maxwell Telescope. Data are from Jorstad et al. (2005).

engine, as in the magnetic launching model of Vlahakis & Königl (2004). This explanation for the displaced core works under certain conditions connected with the relationship between the increase in bulk Lorentz factor and the lateral expansion of the jet (see Marscher 1980). A prime prediction of this model is that the cores of radio galaxies whose jets are viewed at an angle $\gg \Gamma^{-1}$ should lie at the base of the jet if electrons are accelerated there. This implies that there should be a very short gap between the start of the jet and the beginning of the counterjet, except for a limited section obscured by free-free opacity in the accretion disk. Furthermore, the flow should start out fairly broad and become more collimated as it accelerates downstream. VLBA observations of the radio galaxy M87 — whose very massive black hole ($\sim 3 \times 10^9\ M_\odot$; Ford et al. 1994;

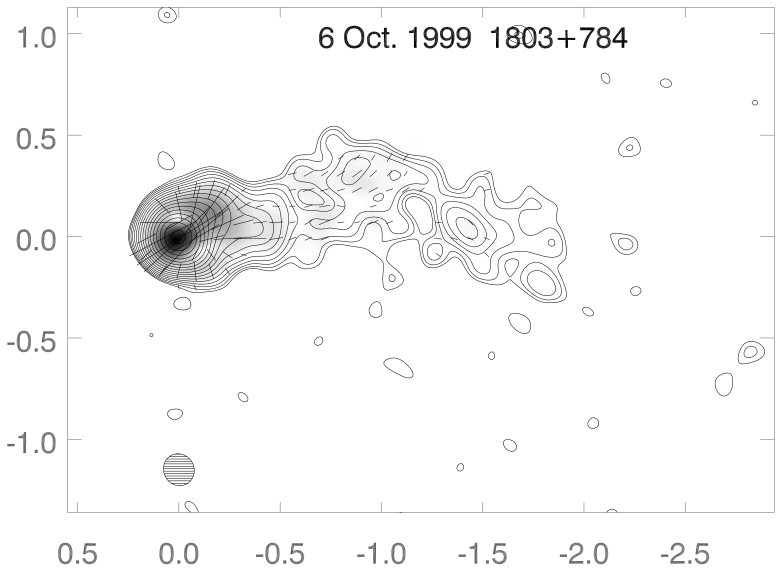

Figure 2. VLBA image of the BL Lac object 1803+784 at 43 GHz. The core is the feature on the eastern end (*left*) of the jet. The polarization vectors are indicated by the line segments. Note the radial geometry of the polarization in the core region, indicating that the magnetic field is, on average, circumferential. The pattern is similar to that obtained for conical shocks by Cawthorne (2006). Data are from Jorstad et al. (2005).

Harms et al. 1994; Macchetto et al. 1997) and relatively short distance allow a linear resolution of tens of gravitational radii — indicate that the flow is indeed quite broad near the central engine (Junor, Biretta, & Livio 1999).

In some objects the core could be a point where the jet bends such that it is more aligned with the line of sight. This is a way for the Doppler beaming factor to reach a maximum downstream of the point where the Lorentz factor attains its asymptotic value. Such a situation should be fairly rare, however, since there is a higher probability that a jet will bend away from the line of sight than into the narrow cone of more aligned directions.

Another possibility is that the core is a conical "recollimation" shock that accelerates particles and amplifies the component of the magnetic field that is parallel to the shock front without decelerating the flow too severely (Daly & Marscher 1988; Gómez et al. 1995; Bogovalov & Tsinganos 2005). This idea agrees with the polarization structure seen in some cores of northern blazars for which the resolution beams are not far from circular (Jorstad et al. 2007), as predicted by Cawthorne (2006). Cawthorne's simulated images are calculated from a model jet with a turbulent (i.e., with random ambient magnetic field direction) plasma passing through a conical shock in a jet viewed at a small angle to the line of sight. In some cases (see Fig. 2 for an example), the polarization electric vectors are aligned radially from the centroid of the core.

The variation of percent polarization across the core region can be matched by this model as well.

There may be multiple conical shocks that form a sequence in the jet, as occurs in gas dynamical simulations when the jet is circularly symmetric (Gómez et al. 1995). In this case, the most compact feature in the jet if it could be imaged at $\nu = \nu_{\rm m}$ would then be the first conical shock, while at lower frequencies the secondary standing shocks would be prominent. Indeed, VLBI images at various frequencies have revealed that stationary features downstream of the core are common (Jorstad et al. 2001; Kellermann et al. 2004; Jorstad et al. 2005). In addition, the non-universality of the frequency-dependent core position mentioned in the previous section implies that the core might be a feature of the flow rather than an optical depth transition point in many jets.

4. Multiwaveband Polarization Variability as a Probe of the Core

If, as indicated above, the core is often a standing conical recollimation shock, with turbulent jet plasma flowing through it, we should see a definite polarization signature. The core should be weakly polarized at 43 GHz, with fluctuations in both degree and position angle of polarization. Indeed, the cores in polarized intensity VLBI images at 43 GHz all have polarization less than a few percent, except sometimes when a new superluminal knot is emerging (Lister & Smith 2000; Marscher et al. 2002; Lister & Homan 2005; Jorstad et al. 2005).

In order to check on variability of the polarization, the author's group and collaborators observed some blazars intensively over an 11-day interval in 2005. The campaign included four VLBA images at 43 GHz and optical measurements on 9 out of the 11 nights. The most telling result came from the quasar 0420−014, the data for which are shown in Figure 3 (D'Arcangelo et al. 2007). The optical polarization position angle $\chi_{\rm opt}$ rotated by about 140° over 10 nights, while $\chi_{43\ \rm GHz}$ rotated by about 80°, in step with the optical rotation, over a shorter period of time. Both the fluctuations in degree and position angle of polarization are consistent with variations caused by many cells of randomly oriented magnetic field passing through the emission region, with some fraction of the cells exiting and others entering between each observation (Jones et al. 1985; Jones 1988). A simulation by the author similar to that of Jones et al. (1985) indicates that apparent rotations of χ by more than 100° are in progress $\sim 10\%$ of the time, simply by random chance, when ~ 600 cells are involved in the emission at any given time. A signature of turbulence is that the polarization does not smoothly rotate, but rather in a choppy fashion, as was the case for 0420−014 (see Fig. 3). [Kikuchi et al. (1988) observed a similar rotation of χ at both optical and radio wavelengths in OJ287, but offered a different interpretation owing to an offset of χ between the two wavebands.]

In order for the value of χ to vary randomly by more than 100°, the conical shock system cannot add a significant steady component to the polarization from compression of the turbulent field across the shock front. This is avoided by the circular symmetry when the viewing angle is very small (Cawthorne 2006), as is the case for 0420−014 (3°; Jorstad et al. 2005). The implication is that the polarization of the core should be steadier for jets observed at wider angles, beyond that which gives the maximum apparent superluminal motion.

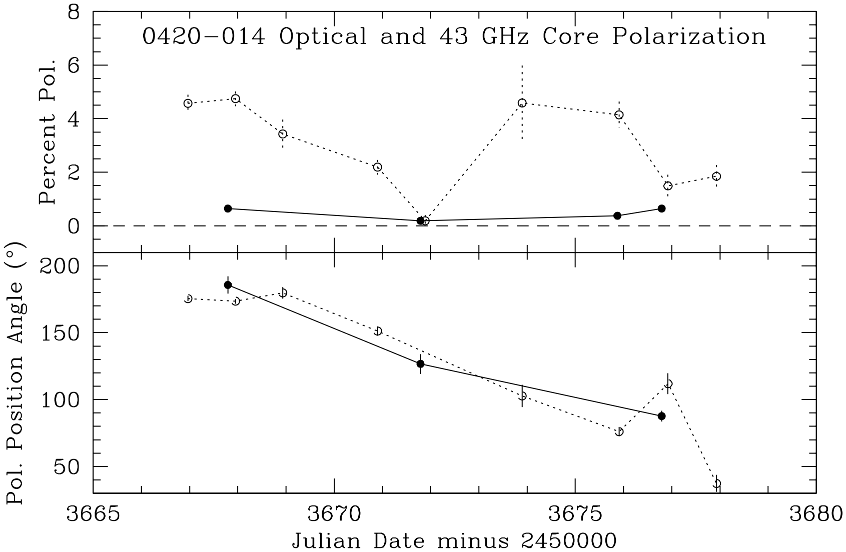

Figure 3. Polarization of the quasar 0420−014 during an observing campaign in late 2005. (Julian date 2453675 is 2005 October 31.) The solid circles correspond to the core on 43 GHz VLBA images. The open circles are optical data measured at the Steward Observatory 1.55 m Kuiper telescope. The position angle cannot be determined at the lowest optical polarization (JD 2453671). The position angle of the core varied by about 90° during the VLBA observation on JD 2453675, and is not displayed in order to keep the figure readable. Data are from D'Arcangelo et al. (2007).

Besides shedding light on the nature of the core, the synchronous variation of the optical and radio polarization position angles demonstrates that the emission at 43 GHz and in the optical bands is co-spatial. Actually, since the degree of polarization at 43 GHz is lower than that in the optical band, there must be an additional, essentially unpolarized radio component. Nevertheless, it means that most of the optical radiation comes from the millimeter-wave core rather than from farther upstream in the jet. Jorstad et al. (2007) find that there is a closer connection between the 43 GHz and optical polarization than that at $\sim$ 300 GHz, which they suggest may arise in the region near the edge of the acceleration zone.

5. Conclusions

The feature that we identify as the core of a jet probably represents different phenomena at different frequencies. At centimeter and long millimeter wavelengths, it is either the $\tau \sim 1$ surface or a standing conical recollimation shock a bit farther downstream (or a blend of both). If we can extend high-quality VLBI imaging to wavelengths of 1-2 mm, we should be able to get a glimpse of the jet at or near the acceleration and collimation zone, where the main radiation probably occurs at IR and sub-millimeter wavelengths. The zone itself is probably best observed in jets viewed at wider angles than is the case for blazars, e.g., as in Cygnus A (Bach et al. 2005) and M87.

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